# Broadband high energy diode pumped Yb:KYW multipass amplifier

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We report a diode pumped Yb:KYW amplifier delivering up to 27 mJ pulses at a repetition rate of 100 Hz and a spectral bandwidth of 5.5 nm, centered at around 1030 nm. The system is based on a double-head multipass amplifier configuration where the pump thermal load is distributed over two relatively thin laser crystals which permits a sufficiently large number of passes with minimal passive losses thus maximizing the energy extraction efficiency. The amplified pulse bandwidth theoretically supports 340 fs pulses and as a demonstration, a small fraction of the amplified pulses has been compressed to 560 fs. 

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Ultrafast diode pumped laser systems are of great interest either as direct high intensity systems or as pump sources for OPCPA based systems operating in the extremely short pulse duration regime. Yb-doped materials, due to the excellent $Yb^{3+}$ ion's spectroscopic properties as well as their thermal management advantages have been extensively investigated in this general context [1]. The most widely studied material is Yb:YAG as it combines both high gain and high thermal conductivity that has recently resulted in the amplification of picoseconds pulses to the Joule level [2-4]. The main limitation however of this material is the available amplification bandwidth, which in the case of high energy systems, restricts its application in the ps regime. Yb:$CaF_2$ on the other hand is a very promising material mainly because of its broad gain bandwidth and high energy storage capacity. Regenerative amplification to several mJ in the kHz regime, both at room temperature and for cryogenically cooled crystals [5,6], as well as Joule level amplification in the femtosecond regime at 10 Hz [7] have been recently demonstrated. The main limitation in this case is the very high saturation fluence of Yb:$CaF_2$, resulting in low gain amplifiers or reduced energy extraction efficiencies. Ideally Yb:$CaF_2$ could be used in the final energetic stages of an amplification chain seeded by a sufficiently high energy, broadband signal to fully exploit its advantages. On the other hand, Yb-doped tungstates (Yb:KGW, Yb:KYW, Yb:KLuW) are well known both for their high gain and broad bandwidth and seem to be the right alternative towards a medium energy level amplification of broad bandwidth pulses. But due to their relatively limited energy storage capacity (with an upper state lifetime of 300 μs) they have been so far restricted to relatively low energy applications at high repetition rates.

In the framework of the Institut de la Lumière Extrême (ILE) project and the 10 PW Apollon source front end development, we study the development of a 100 Hz broadband Yb:KYW multi-mJ level ($\Delta\lambda$>3.5 nm, E>20 mJ), multipass preamplifier for Yb:$CaF_2$ based main amplifiers to reach the required final Joule level output.

Several works have been reported on Yb:KYW or Yb:KGW in both regenerative and multipass configurations. The highest energy achieved so far from a diode pumped system based on a cryogenically cooled Yb:KYW regenerative amplifier, has been limited to 5.5 mJ [8], while pulses as short as 190 fs have been reported for sub-mJ setups [9]. 25 mJ pulses have been also reported but based on a low efficiency and complex Ti:Sapphire pumped Yb:KGW regenerative amplifier operating at 1 Hz [10].

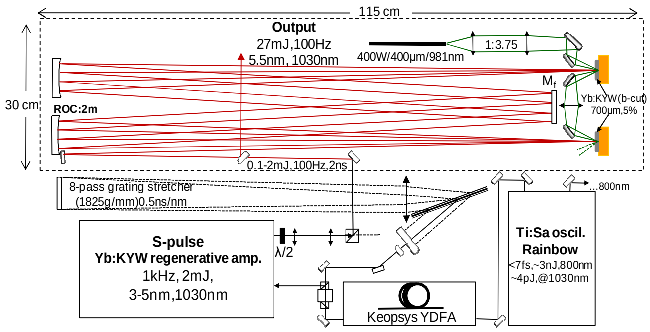


Fig. 1. Experimental setup. Schematic of the CPA injection system (bottom part). Double head Yb:KYW multipass amplifier (upper part).

In this study, we present a multipass amplifier based on a diode pumped Yb:KYW crystal operating at room temperature and delivering pulses with energies up to 27 mJ at 100 Hz (2.7 W average power). This is the highest energy ever reported for a Yb:KYW based amplifier. The overall optical-to-optical efficiency of the system is around 15% with an extraction efficiency estimated to be greater than 70%. The achieved bandwidth at the maximum energy is 5.5 nm, corresponding to 340 fs Fourier transform limited (FTL) pulses which, when compared to previously reported results, is an improvement by a factor of at least 2 for this type of amplifier and energy level.

In Figure 1, the general schematic of the complete chirped pulse amplification (CPA) chain studied here is presented. The starting point is a very broadband Ti:Sapphire (Rainbow from Femtolasers) oscillator delivering sub-7 fs pulses at 800 nm with a spectral content that is well extended in the 1030 nm regime. About 4 pJ pulses around 1030 nm are filtered and separated at the output of the oscillator. These pulses are first amplified in a Yd-doped fiber amplifier (Keopsys) to 4 nJ and then stretched in a classical double pass grating stretcher (stretching factor: 0.5 ns/nm). The following amplifier consists of a diode-pumped Yb:KYW regenerative amplifier (Amplitude Systemes) delivering pulses up to 2 mJ. The repetition rate of this amplifier is adjustable up to 1 kHz while the output spectrum can be finely tuned by an intracavity polarizer. In these experiments, the repetition rate was fixed at 100 Hz and the output spectrum was centered at 1030 nm with a bandwidth of 4.5 nm.

In the upper part of Fig.1, we present a detailed design of the amplifier under study. The amplifier is very compact, covering an area of only 1.15x0.3 $m^2$. The whole CPA setup could fit in less than half of an optical table. It is composed of a simple folded 4f imaging cavity where two laser crystals are used as end mirrors. The laser crystals are two identical 0.5° wedged, 5x5mm Yb:KYW disks of 700 μm thickness at b-cut (E//a) and 5% doping level. The crystals are soldered on a metal mount that is cooled by circulating water at about 18 °C.

The specific cavity design permits both a large number of passes with minimal losses, but most importantly, the combination of two relatively thin amplifying disks that results in the pump thermal load distribution. As shown in Fig. 1, the crystals are pumped in series by a unique fiber coupled diode with a 400 μm core diameter, delivering up to 400 W at 981 nm (LIMO). The diode operates in QCW regime with variable repetition rate and pulse duration, allowing the fine temperature adjustment of the emission wavelength exactly to 981 nm (to match the absorption peak of Yb:KYW), with ~3.7 nm bandwidth. The repetition rate in these experiments is set at 100 Hz and the pulse duration at 450 μs, corresponding to 180 mJ pulse energy (18 W). At maximum pump power, about 135 mJ (75%) are absorbed in both crystals (~86 mJ in the first crystal and 49 mJ in the second one).

Only about 37 mJ is estimated to be the actual total stored energy. This is not surprising since for the relatively high incident pump intensity of more than 22 kW/$cm^2$ (5 times the saturation intensity of the Yb:KYW for unpolarized pump), the effective storage time is reduced to $\tau_{sto} \approx 50$ μsec ($\tau_{sto} = \tau_{fluo}/(1+I_p/I_{sat})$). The 450 μsec long pump pulses were chosen however in order to increase the stored energy (with an upper duration limit set by the crystals thermal load) but at the cost of decreasing the global energy storage efficiency.

In the optimal cavity configuration, the beam passes 11 and 10 times through the first and the second crystal respectively (a complete round trip inside the crystal is counted as one pass). Both pump and signal diameter on the crystals planes is 1.5 mm. The cavity is optimized by adjustment of the folding mirror ($M_f$) position to compensate the induced lensing by the laser disks estimated (at maximum pump power) around 10-12 m. The cavity passive losses have been estimated at ~15% by replacing the two crystals with high reflection mirrors. The amplifier operates in air environment and no vacuum is required.

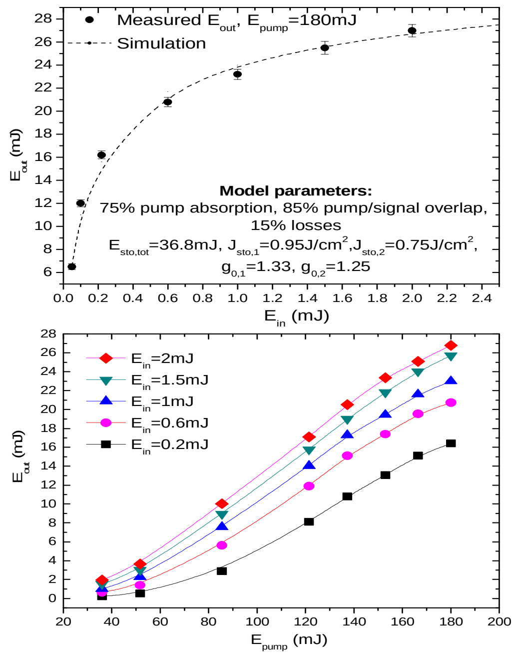


Fig. 2. a) Output energy as a function of the input energy for maximum pump energy (180 mJ). The dashed line curve corresponds to the simulated output ($E_{sto,tot}$: the total stored energy, $J_{sto,1/2}$: the stored fluence for each crystal, $g_{0,1/2}$: the small signal gain coefficient for each crystal). b) Output energy as a function of the incident pump energy for different input pulse energy at 100 Hz.

In Figure 2a, we plot the the output energy as a function of the signal energy at maximum pump power. We also plot the predicted (dashed line) output energy based on a Frantz-Nodvik model, taking into account the measured pump absorption and passive losses as well as the calculated total stored energy and its relative distribution in each crystal (model parameters are indicated in the figure). For a 2 mJ input, we obtained 27 mJ at the output, well into the saturated, energy extraction regime of operation of our amplifier. In Figure 2b, we plot the output energy as a function of the total incident pump energy for various input pulse energy levels (0.2-2 mJ) at 100 Hz. For 140 mJ pump power, we observe the reduction of the efficiency slope due to the pump absorption saturation and energy storage efficiency reduction. It is also interesting to notice that the output energy barrier of 20 mJ is still surpassed for ~0.5 mJ input (40x gain). At maximum output energy the global efficiency is 15% and the extraction efficiency ~72%.

In Figure 3, the input and output beam profiles of the amplifier are given for increasing pump energy. The $M^2$ of the beam was optimized for maximum pump power and measured to be better than 1.2 in both directions (1.1 for the input beam), indicating a high quality output beam. The main difficulty at this point was the rising astigmatism induced by the laser crystal with increasing pump power [11]. For moderate pump power level (<20W), proper orientation of the crystals (common for both crystals) and respecting the E//a polarization direction, could be beneficially used to compensate the small input beam astigmatism (comparison of beam profiles at $E_p$=90 and 180 mJ in Fig. 3). Further increase of the repetition rate was possible up to 200 Hz but with a moderate output energy reduction of 10-15% due to the progressive thermal degradation of the beam quality and increasing crystal temperature. Above 200 Hz however the induced asymmetric thermal lens resulted in strong beam diffraction at the edges of the cavity mirrors and the fast decrease of the output energy.

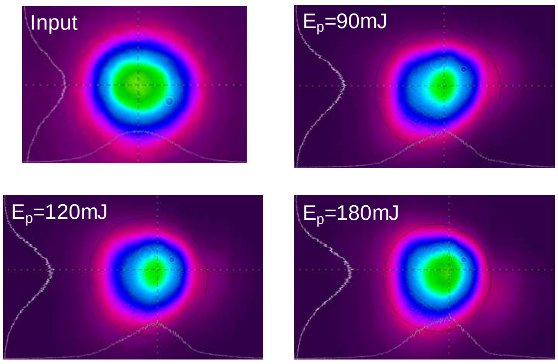


Fig. 3. Input and output beam profiles (near field) for 90 mJ, 120 mJ and 180 mJ pump energy at 100Hz ($E_{in}$=1mJ).

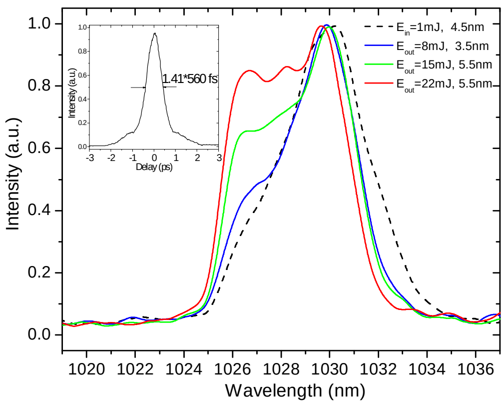


Fig. 4. Output spectrum as a function of the output energy for $E_{in}$=1mJ (dashed line curve corresponds to the input spectrum). Inset : autocorrelation trace of the recompressed pulses at 22 mJ.

The stability of the system has been also examined. At 27 mJ output and over 20 minutes, the pulse-to-pulse rms variation was measured to be 0.8% (0.4% at the input). The beam pointing stability was found <50 µrad.

The evolution of the output spectrum as a function of the output energy is also examined. In Figure 4, we plot the input/output spectra for 1 mJ input energy and for 8 to 22 mJ output energy. We observe the spectrum progressive blue shift towards 1025 nm, resulting in a rectangular-like spectrum of 5.5 nm bandwidth at 22 mJ. This behavior is the combined result of (i) the Yb:KYW (E//a) gain peak around 1025 nm, (ii) the gain saturation in combination to the CPA that counteracts the blue shift and (iii) the specific spectral form of the input pulses centered at 1030 nm, extending to almost 1025 nm. This spectral bandwidth corresponds to about 340 fs FTL pulses. As a demonstration of the compressibility of these pulses, based on a matched grating compressor, a small fraction of the output (few µJ) has been compressed around 560 fs (Fig. 4 inset), about 1.6 times the FTL duration This deviation is most probably due to the complicated higher order spectral phase generated in the Ti:Sapphire oscillator in the 1030 nm regime.

In conclusion, we presented the development of an Yb:KYW multipass amplifier that delivers broadband pulses of 5.5 nm on a record energy level of 27 mJ. The system operates at a high repetition rate of 100 Hz, providing 2.7 Watts of average power with an excellent beam quality. Scaling of the amplifier performance in terms of output energy seems to be possible based on the use of slightly thicker crystals. According to our model, replacing both crystals with 1 mm thick crystals would result in more than 50 mJ output energy. The repetition rate in this case, could be maintained at 100 Hz with a carefully designed cavity and proper cut of the crystal to compensate the astigmatic thermal lens [11].

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